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Experimental Study on the Differential Hybrid System Hybrid Electric Vehicle

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Abstract

By the transmission analysis of the traditional symmetrical bevel gear differential which is acted as the power coupler, we had built the mathematic model, and also built the test-bed, and took simulation test by the NEDC condition. First in the traditional differential coupling test, it appeared power transfer of abnormal and component damage. After analysis the results of the rotational speed, torque and friction power, we retrofitted the test, at this time, it did not appear unusual, and also can reliably transfer power and take differential coupling, and improve the sliding friction work and heat concentrated significantly. This validated the feasibility and effectiveness of differential hybrid system applying in hybrid electric vehicle.

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Keywords: Hybrid Electric Vehicle, Differential Hybrid System (DHS), Experimental Study;

1. Introduction

Power-split device is one of the key components of hybrid electric vehicle, which depends on the vehicle best performance can be realized or not. At present, the international used it the most successful on hybrid electric vehicles is the Toyota company development "PRIUS" hybrid vehicles, and its dynamical coupling form is typical of planetary gear PSHEV, this structure has electronic continuously variable transmission (ECVT) function., can make each sources of power control flexibility, and make the whole system do the best performance^[1-4]. The earlier research topics present a novel differential PSHEV dynamic coupled system, it also can make the engine and road load power completely mechanical decoupling, make the system efficiency best^[5-7]. The upfront simulation results show that the traditional

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differential applied as differential hybrid system in the hybrid electric vehicles is feasible [8, 9]. This paper will focus on traditional vehicle differential as the power-split device in the hybrid electric vehicle, and its structure of application deeply on the experimental research.

2. Differential Hybrid System Work Principle

2.1. Differential hybrid system configurations

The symmetric bevel gear differential applied as differential hybrid system in the hybrid electric vehicle as shown in figure 1: the left half axle gears 1 and generator is linked together, driven bevel gears 2 (corresponding planets frame) and active bevel gear mesh and driven by the engine, right axle gears 3 through motor coupling, output torque to drive wheels.

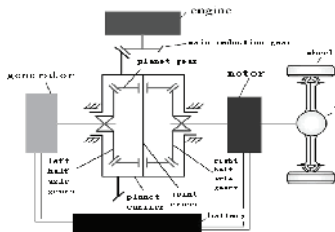


Figure 1 The symmetric bevel gear differential hybrid system

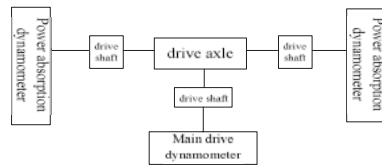


Figure 2 The structure of drive train bench test

2.2. Differential coupled hybrid transmission characteristics

For the convenient of study, we can hypothesis engine to the planet shelf transmission ratio of 1. Then the speed meets the type as follows.

$$\omega_1 = \omega_g, \omega_2 = \omega_e, \omega_3 = \omega_m \quad (1)$$

Meanwhile each port respectively corresponds to each of power torque, namely

$$T_1 = T_g, T_2 = T_e, T_3 = T_L - T_m \quad (2)$$

In the type: $\omega_g, \omega_e, \omega_m$ respectively for generator, engine and motor speed. T_1, T_2, T_3 respectively for left half axle gears, driven bevel gears and right half axle gears torque. T_g, T_e, T_m, T_L corresponding generator charging torque, engine transfer to the driven bevel gear torque, motor output torque and load torque

If ignored its internal friction loss, symmetric bevel gear differential features: half shaft speed can be differential, and torque is the same, i.e.

$$T_3 = T_1 \Rightarrow T_g = T_L - T_m \quad (3)$$

Further according to power balance equation:

$$T_e \omega_e = (T_L - T_m) \omega_m + T_g \omega_g \quad (4)$$

$$\text{and: } 2 \omega_e = \omega_m + \omega_g \quad (5)$$

The two output shaft torque for:

$$T_g = T_e / 2 \quad (6)$$

Namely generator charging torque fixed for half of the engine torque, the surplus of torque supplied by the motor.

$$T_m = T_L - T_e / 2 \quad (7)$$

From the above analysis, we can conclude that the known speed (with wheels constant speed connected motor speed ω_m), can be adjust the generator speed ω_g , and then determine the optimal engine set-point speed ω_e . For the relationship of torque, after we fixed engine optimal load point, and through adjusting the generators, motors load, it can satisfy the vehicle speed and load demand, so as to achieve the electronic continuously variable transmission (ECVT) function. Specific regulation relationship of the power output for: by formula 6 and 7, by controlling the generator charging torque, we can determine the engine torque requirements for its twice, generator energy storage by generate electricity, could provide pavement load torque requirements through the motor assistance power.

3. Experimental Study on Differential Hybrid System

3.1. Differential hybrid system test plan

Based on the above analysis of differential hybrid system connect relation and with power transfer characteristics, the simulation research of differential coupled device applying in HEV have done by references [8], and the ultimate feasibility was validated in theory. On the basis of the simulation study, this paper focuses on the experimental research. Experiments were designed with three terminals dynamometer of the drive train test-bed simulation in Europe NEDC condition (3/4 discharge standards type test conditions, and the same to GB18352.3 (the state 3/4)) the three terminals rotational speed and torque of the differential coupler hybrid electric vehicle, and then compare with the theoretical analysis, to verify the rationality of this system.

First utilizing HEV power train simulation model in the ADVISOR, according to the practical demands emulation produce the extremities speed and torque of differential coupled device in working conditions, we can formulate experiment scheme. And then we could through three terminals speed and torque based on the modified model in NEDC working conditions, to select representative operation point, formed to test plan that can complete reflect working condition of differential coupled device.

Specific steps of the test are as follows: 1) Differential assembly as figure 2 installed to drive train bench test. 2) Start test-bed control device, honing differential assembly. 3) According to the test plan, change the input torque and speed. 4) Acquisition and record the output torque and speed. 5) After test completion, remove test device, inspection the test results. 6) To conduct the follow-up test data processing and analysis.

3.2. Differential hybrid system prototype test

By the original differential structure that does not make any modification, according to table 1 test plan and the above mentioned for steps, we can take the test, and examine the original differential can be meet its application in differential dynamic coupling of the hybrid electric vehicle requirements or not.

Table 1 Differential coupled device test plan

Speed (km/h)	5	10	15	20	25	30	35	40	45	50
Left half shaft speed (rpm)	181.6	363.2	544.8	726.4	908.0	1089.6	1271.3	1452.9	1634.5	1816.1
The input speed (rpm)	0	0	0	0	3000	3000	3000	3000	4000	4000
Right half shaft speed (rpm)	181.6	-363.2	-544.8	-726.4	626.8	445.2	263.6	82.0	412.0	230.4
Left half shaft torque(Nm)	-10	-60	-60	-65	-65	-65	-65	-65	-65	-50
	-30	-25	-40	-40	-35	-35	-20	-20	-20	15
	65	-20	100	70	75	10	15	70	70	60
	85	70		80	90	80	65			
	100	100		85		90				
		120								

Chart 3 is connection object graph of test-bed.



Figure 3(a) Differential link the three dynamometers



Figure 3(b) Planetary shaft and shell agglutination

3.2.1. The experimental phenomena

The test continuously, at speed of 5 km/h, 10 km/h, until 15 km/h, then I heard differential abnormal noise, stop the test. Dismantled Main reducer and removed the differential, we found the planetary shaft and shell have been agglutination, as shown in the following figure 3(b).

3.2.2. The analysis of the experimental phenomena

Figure 4(a)、figure 4(b) respectively is the relationship of speed and torque in the original structure differential test (10 km/h) sites.

Judging from the curve, speed is to satisfy the type (5) relationship, such as the input speed is close to zero, the speed in output terminal 1 and output terminal 2 basic opposite. Test results and data shows that the relationship of speed that was established by the differential coupled. Similarly, the torque can also satisfy the differential equation of torque.

From the above test, the relationship of power should satisfy: $P_2 = P_1 + P_0$. At this time, output terminal 2 is power output, and because input speed ω_0 control of its output is small, theory is 0, it should be approximation $P_2 = P_1$. But due to differential bigger, internal friction power was exist, can led to their will have a difference. In case normal small differential, the friction torque T_f is very small, friction power should be small too. But we must pay attention to the current high differential, and actual friction power will be very big.

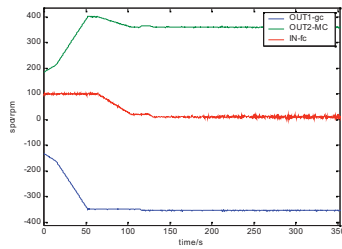


Figure 4(a) The relationship of speed in the differential test

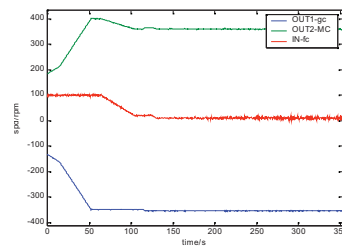


Figure 4(b) The relationship of torque in the differential test

And the friction torque: $T_r = T_2 - T_1$ (including T_1 T_2 respectively for the torque of generator, motor). And internal friction torque in the test to see chart 5(a).

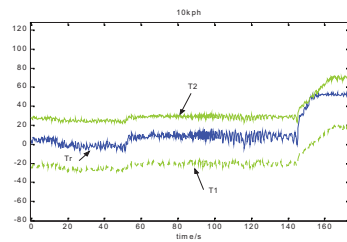


Figure 5(a) Internal friction torque,

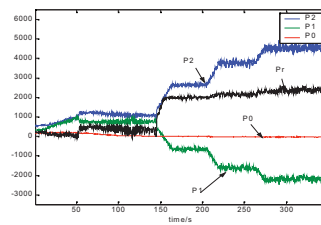


Figure 5(b) Output power

From the above the test and analysis curve, at begin the friction torque were small, only 0-20 *Nm* or so, then friction torque increase and differential high, such as shown above figure 5(a). So the three terminals output power calculations are shown in the following figure 5(b).

This power curve explanation: the power input by P_2 , a large part consumed by the internal differential friction, from these above curves, right now the average friction power was 2212 *watts* (from above curve between 180 seconds and 340 seconds).

The above test explanation: because there's a large friction consumption, and lubrication effect improve not effectively, make its heat concentrated. And because of the original structure is not to make any changes, namely planetary shaft and planetary gear, planetary gear and shell are sliding friction, easy in high-speed differential produce a lot of heat, again have no good lubrication adopted timely, and the original splash lubrication effect is poorer. Therefore, between planetary shaft and gear, planetary shaft and shell emerge agglutination. Thus the original differential cannot satisfy the use requirement as power couple device in hybrid electric vehicle.

3.3. Differential hybrid system retrofit test

For the first round of test, at the speed point 15 *km/h*, it appeared abnormal noise, planetary shaft and shell agglutination phenomenon. For the structure of the local improvement, we applied a simple method to make it meet this high difference speed applications. Here instead rolling for sliding, namely, it puts forward the improved methods as follows.

Specifically, we can assembly needle between the differential planetary gear and the gear axis to improve the friction relationship of their relatively high-speed operation. In order to reserve needle installation space, we need to be re-machined differential planetary shaft, and take proper heat treatment

for the planetary gear holes and re-machined planetary gear shaft. At the same time, for preventing needle peel, the needle two terminals relying on processing shaft shoulder of differential planetary gear shaft to guarantee.

According to above plan, we had designed the planetary gear, and assembly differential, still in accordance with table 1 test plan to do a second test.

3.3.1. The experimental phenomena

During the test, it appeared sound, then we stopped the test, and found the temperature was not high, while idling not hear abnormal noise, therefore, we thought the gears no problem. Then we carried on the second test, but in this time, it appeared a lot of noise. Then stopped the test, we discovered that while idling it had very big noise. Ravel differential, the test results are shown below, and planetary shaft broke four sections.

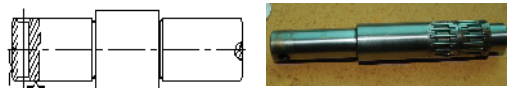


Figure 6 A second experiment phenomenon--gear shaft fracture

Figure 7 Planetary shaft retrofit structure design

3.3.2. The analysis of the experimental phenomena

Similarly, take the above-mentioned test one for example (for a corresponding speed of 10 km/h point), processing method is the same as above. Among them, the speed and torque still meet equation, here no longer list.

The internal friction torque as below:

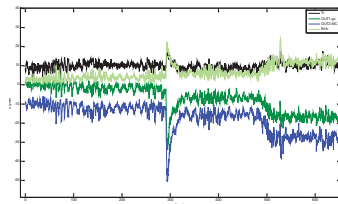


Figure 8(a) Internal friction torque,

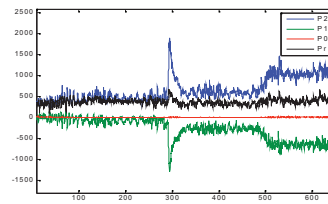


Figure 8(b) Output power

From the above test and analysis curve, at begin the friction torque were small, only 10 Nm or so, such as shown above figure 8(a). So the three terminals output power calculations are as shown in the following figure 8(b).

These above curves shows: the internal friction torque relative for original scheme, at the same differential point, the friction power of original plan for: 2212 watts. And from the improved test situation, namely from these above curves to see, the average friction power for 375 watts (above curve between the 100 seconds and 600 seconds). Visible, the improved scheme is obviously better than the original plan,

namely after the sliding friction instead rolling friction, internal friction power of differential improved 83%, such as shown in table2.

Table 2 The contrast to friction power in the rounds test

Test plan	friction power (w)	Improve degree (%)
the first round test(<i>the original</i>)	2212	
e second round test(<i>needle roller</i>)	373	83%

Through the above analysis of the friction power, we can conclude that retrofit scheme in change of sliding friction for rolling friction, resolve internal friction and thermal aspects increased significantly. And in the original design scheme, planetary shaft appeared cracking phenomena on the four needle interfaces, because the groove center circle diameter with planetary gear inner hole diameter (outside groove diameter) to outside offset 0.09 mm, eventually leading to the needle circumference total clearance become excessive big and between needle and needle happened movement interference.

3.4. The third retrofit test

Aiming at the needle happened offset in the second retrofit test, research proposes the choice with maintains and without internal and external groove of K class needle bearing (K16x20x13 needle bearing) and install to the planetary shaft, make the original sliding into rolling. For normally assembly, we need take the planetary shaft two sides outside shaft shoulder refitted into round sleeve, which one side need to machine pin hole, used for locating pin fixation. Planetary shaft need to be redesigned and processed, still use 20CrMnTi material, in order to correct coordination, its two terminals without shaft shoulder as shown in the following figure 7.

In order to validate differential coupling dynamic device retrofit test effect, we still accordance with the front experiment steps and the follow table 3 scheme to do the third test, and the results are ideal, did not appear abnormal noise.

Table 3 Differential coupled device third trial scheme

Speed (km/h)	5	10	15	20	25	30	35	40	45	50
The input speed (rpm)	0	0	0	0	3000	3000	3000	3000	4000	4000
Right half shaft speed (rpm)	-182	-363	-545	-726	627	445	264	82	412	230
Left half shaft torque(Nm)	100	120	100	85	90	90	65	70	70	60

In the test results, speed and torque still meet the above relations and the friction power were similar to the second experiment, here no longer list. The experiment proved upon differential coupled device further retrofit, the left、right half axle gear already can adapt to continued high rotation speed difference operating conditions, and internal various parts of differential no obvious failure phenomenon. According to the test plan in table 3, further verify the new differential coupled device can normal work under the conditions of each speed range and big load torque.

Visible, the further retrofit scheme can meet the test requirements well.

4. Test Results Compared And Analyzed

The fracture phenomenon of the second pure needle improvement scheme, main may be stress concentration existing planets axis machining, make fractures all appear at four needle interface. And it did not appear agglutination phenomenon that in the first round of original structure test, illustration that

the second retrofit scheme on improving Sliding friction power aspects have obvious effect, cracking phenomena should still from structure processing and materials be guaranteed.

The third round test results show that the improved scheme to improve thermal concentration effect obviously, and because of needle to keep, the cracking phenomena of original plan was assured from structure processing, make test experience many conditions of circulation and large load test, the test procedure wear is small. The test parts remain intact. This validated the feasibility and efficiently of the differential coupled device applied in the hybrid electric vehicle in the third round improvement scheme.

5. Conclusion

This paper adopt the traditional symmetric bevel gear differential as dynamic coupled device of hybrid electric vehicle, and analyzed the differential coupled power transfer characteristics and connections, through three dynamometer simulated the three power sources engine, motor and generator, built the test bench and took the simulation test by the NEDC condition. After the test of the original differential used as power coupled device, emerge the planetary shaft and shell agglutination phenomenon. In its original structure add needle and after improvement of the planetary gear shaft, we had taken the second round of the test, the test results appeared planetary shaft fracture phenomena, that is because the needle happened offset then cause thermal concentration, but it improved friction work significantly.

For the defect of the second round test, in its original structure add maintains rolling bearings and after improvement of the planetary gear shaft, we had taken the third round of the test. The test results was good, and did not appear unusual, it can reliably transfer power and differential hybrid coupling, and improve the heat concentrated significantly. Through analyze the results of speed, torque and friction power, we concluded that: the further retrofit symmetric bevel gear differential applied as power-split device of hybrid electric vehicle, which can meet the needs of its height difference speed, and can abandon transmission and clutch, and has the electronic continuously variable transmission (ECVT) function.

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